Efficient Class-E Power Amplifier for Variable Load Operation

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***Abstract*— In this paper, a GaN HEMT class-E power amplifier (PA) has been designed for efficiently operating under variable load resistance at the 750 MHz frequency band. The desired zero voltage switching (ZVS) of the device can be approximated for a wide range of resistive loads, by means of a simple inductive impedance inverter, derived from [1]. The load-pull contours, obtained from simulations, allowed the drain terminating network to be properly adjusted in order to maximize the output power control while at the same time minimizing losses. Once the amplifier was implemented, an efficiency over 76% has been measured at 9.6 dB power back-off, with a peak of 85% at 50 Ω. In addition, the efficiency stays as high as 75% for a 150 MHz frequency range.**

Keywords—Class-E; efficiency; GaN HEMT; load modulation; power amplifier; UHF.

I. INTRODUCTION

Along the last decade, efficient transmitter architectures have been receiving an ever increased attention. The need for cutting the huge operational costs in base stations and for saving battery in user terminals has determined important efforts by both industry and academia. Thus, techniques which may adjust the PA power consumption to the envelope of the signal, like dynamic biasing or load modulation, have become more common in detriment of the traditional way of operating PAs under fixed voltage supply and impedance conditions.

Load modulation schemes, conceived by Chireix [2] and Doherty [3] for high power AM broadcasting in the 30's, have proved to be valid for efficiently transmitting modern wireless communication signals with large peak-to-average power ratio (PAPR) values. In an outphasing transmitter, each of the two integrating PAs is load modulated by the phase-shift between their constant-envelope excitations, which makes it attractive for the introduction of class-E or alternative switched-mode PAs. Although its original topology in [4] is certainly sensitive to variations in load resistance, several authors have been addressing the design of class-E PA variations with unbeatable efficiency performance under load modulation [5, 6].

In this paper, a GaN HEMT class-E power amplifier, designed for efficiently operating under variable load resistance at UHF band, is presented. Aimed for its use not only in LTE outphasing transmitters, but also in load-invariant resonant DC-to-DC class E^2 power converters [7], a simple lumped-element output terminating network has been adjusted in order to minimize the power losses, approximating a ZVS operation.

II. CLASS-E POWER AMPLIFIER DESIGN

Modifications to the output terminating network of a class-E power amplifier have been addressed since the very beginning [8], leading to the more recent definition in [9] of a continuum of operating modes. In [1], an inductive impedance inverter was introduced for the case of a class-E PA with antiparallel diode. With such a simple topology variation, the range of its no-loss operation could be theoretically extended to load resistances over the nominal value, R_{opt}, avoiding the step change of the switch voltage at turn on as well as the associated switch current spike that could even destroy the transistor when operated in such condition.

Although adding an antiparallel diode may not be a feasible solution for high power PAs at UHF frequencies and beyond (fast enough Schottky diodes able to handle high current and voltage levels are rarely available), the solution in [1] may be adapted to transform a variable load resistance into an impedance locus, as seen from the drain terminal of an RF/microwave HEMT device, quite close to the one assuring power control with maximum drain efficiency.

A. Load-pull Simulations

Load-pull simulations on AWR Microwave Office, Fig. 1, were completed at the fundamental frequency for a 30 W GaN HEMT device from Wolfspeed (CGH35030F), using the nonlinear model provided by the supplier. The higher order harmonics were all terminated in open circuit condition, as typical for the class-E topology proposed by the Sokals when a resonant circuit with enough quality factor is employed [4]. The device was biased at V_{DS} = 28 V in order to avoid the peak value of the switch voltage waveform to reach breakdown (over 120 V for this process). The gate biasing voltage was selected as V_{GS} = -3.5 V, just below observing any increase in the device output conductance. The highest possible input power was applied in order to approximate a switch-mode of operation under a continuous wave (CW) excitation. The appearance of 1 mA of rectified current at gate terminal was used as upper bound.

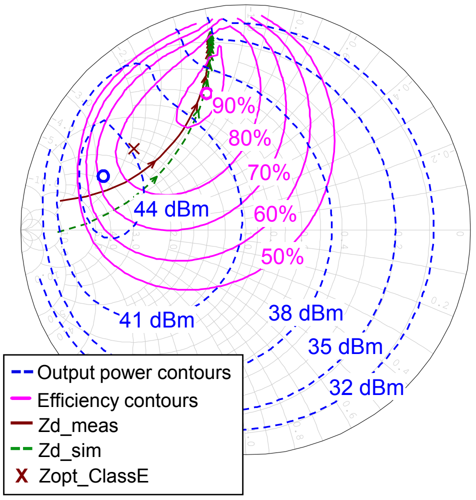

Fig. 1. Efficiency (—) and output power (--) load-pull contours from simulations, together with the simulated (--) and measured (—) $Z_{in}(f)$ evolution with R_L. The theoretical value of the nominal impedance, Z_{opt}, is also shown.

The calculated nominal impedance at 750 MHz, $Z_{opt}(\omega) = 0.28/(\omega\cdot Cout)\cdot e^{(j\cdot 49°)} = 13.17 + j\cdot 15.17\ \Omega$, has been also represented in Fig. 1, together with the obtained load-pull contours for output power and drain efficiency. An optimum trajectory in terms of efficiency, with controllable output power, could be traced over the Smith chart. Such trajectory (not represented for sake of clarity) would include the impedance points resulting in both maximum power and maximum efficiency, being the previously calculated nominal value quite close to it. Using an admittance grid for the Smith Chart, it may be also noticed that the susceptance shows only a small variation along a great extent of that optimum load modulation path. This justifies the selection of an inductive impedance inverter, similar to the proposed in [1].

B. Output Network for Load Modulation

A drain terminating network composed of a series LC circuit (resonating close to the design frequency), together with an inductance to ground, was selected (see PA schematic in Fig 2a). The evolution of its input impedance, obtained from simulations, when varying R_L from 5 to 500 Ω at the highlighted reference plane, has been also plotted over the contours in Fig. 1 (dashed green line).

High Q lumped elements from Coilcraft and ATC were used in the implemented amplifier (Fig. 2b). The 12.5 nH coil (Mini, Air Core Series) self-resonates between the frequency positions of the second and third harmonics, providing a high impedance termination to both of them. The evolution with R_L for the measured output terminating network, shown with a brown trace in Fig.1, is slightly different from simulations. The series capacitor was adjusted in the lab to slightly detune the series resonant circuit, leading to a better performance for low R_L values (upper part of the output power range). The biasing and input matching networks, completing the PA, just follow widely accepted topologies. The chokes, bypassing and decoupling capacitors were selected according to their parasitics and self-resonance frequencies.

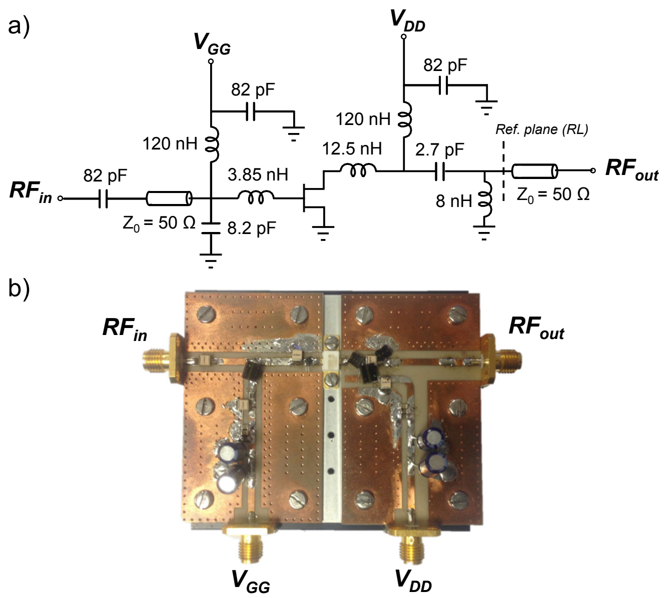

Fig. 2. Designed class-E power amplifier: a) Circuit schematic, and b) photograph with implementation details.

III. PA Characterization

The implemented power amplifier was characterized under CW excitation for both constant (50 Ω) and variable resistive loading conditions.

A. Constant-load Profiles

The measured performance of the amplifier with frequency, under 50 Ω condition, is represented in Fig. 3. The efficiency and power added efficiency (PAE) profiles stay above 75%, along a 150 MHz and a 130 MHz frequency range, respectively. The measured peak of efficiency reached 85% at the design value, 750 MHz, with and output power of 41.4 dBm.

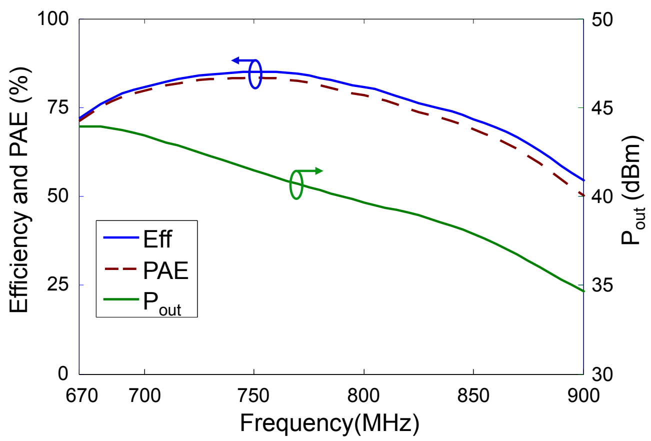

Fig. 3. Measured evolution for the drain efficiency, PAE and output power in terms of frequency.

B. Performance under Variable Resistive Loading

Following the set-up presented in Fig. 4, the PA was characterized under a variable resistive load. A MST981EN Manual Impedance Tuner from Maury Microwave was used to set each desired value for the load resistance at the reference plane (defined at the position of the 8 nH coil). Additionally, a low pass filter was included for avoiding undesired contributions from the remaining content in higher order harmonics to the measured value of the output power.

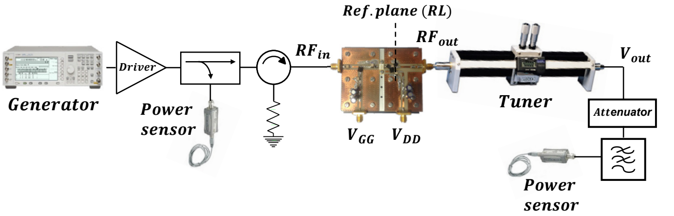

Fig. 4. Measurement set-up for characterizing the PA under a variable resistive load .

As it was expected from simulations, the efficiency evolution with R_L, shown in Fig. 5a, keeps high for a significant power control range. Efficiency values of 76% and 70% were measured at power back-offs as high as 9.6 dB and 10 dB, respectively. This performance is competitive with the results obtained from solutions based on [5, 6].

Finally, the R_L-to-AM static modulation characteristic was extracted from the measured results (Fig 5b). In theoretical terms, the output power of a 100%-efficient PA should vary with the inverse of the load resistance, resulting in a voltage amplitude at the output of the impedance transformer (V_{out} in Fig. 4), linearly following the inverse of the square root of R_L. This is the profile to be approximated when operating this PA as part of an outphasing transmitter.

IV. Conclusion

The design of a GaN HEMT class-E power amplifier, aimed to efficiently operate under a variable load resistance has been presented. Thanks to the use of an inductive impedance inverter, a ZVS operation is approximated for a wide range of resistive loads. A high efficiency (above 70%) is then assured for a significant output power back-off (up to 10 dB). These results make the proposed topology amenable for its use in load modulating transmitter architectures, as outphasing (Chireix). Advantage may be also taken from its low losses for implementing a nearly self-regulated DC-to-DC converter.

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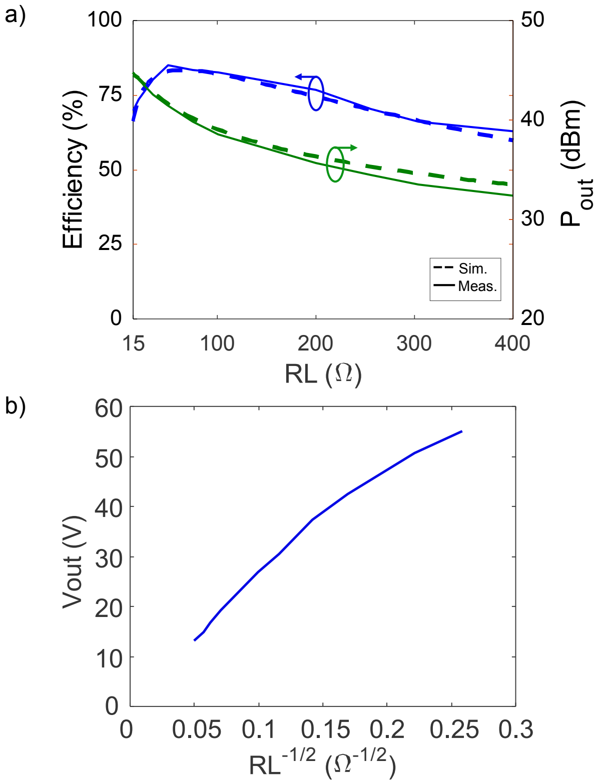

Fig. 5. a) Measured (—) and simulated (--) profiles for drain efficiency and output power with R_L b) Output voltage evolution with the inverse of the square root of R_L.

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